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FINAL REPORT

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A. Gordon Emslie, Principal Investigator

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This report covers activities on the above grant for the period through the end of September 1997. The work originally proposed to be performed under a three-year award was converted at that time to a two-year award for the remainder of the period, and is now funded under award NAG5-4027 through Goddard Space Flight Center.

The P.I. is a co-investigator on the High Energy Solar Spectroscopic Imager (HESSI) team, selected as a Small-Class Explorer (SMEX) mission in 1997. He has also been a participant in the Space Physics Roadmap Planning Group. Our research has been strongly influenced by the NASA mission opportunities related to these activities. The report is subdivided into four sections, each dealing with a different aspect of our research within this guiding theme. Personnel involved in this research at UAH include the P.I. and graduate students Michele Montgomery and Amy Winebarger. Much of the work has been carried out in collaboration with investigators at other institutions, as detailed below.

(1) Structure of Electrical Currents in Solar Flares

It is well-established (e.g., Holman 1985, *Ap. J.*, **295**, 584) that a single, unidirectional current distribution cannot be responsible for the huge currents associated with the hard X-ray producing electrons in the impulsive phase of a solar flare. The use of cospatial return currents (e.g., Emslie 1980, *Ap. J.*, **235**, 1055) is effective only for stochastic acceleration mechanisms, since mechanisms involving direct electric field acceleration cannot admit such a return current in the acceleration region itself. Therefore, one must postulate a large number ($> 10^6$) of oppositely-directed current channels in the impulsive phase.

Holman (1985) originally suggested that this result necessitated the preflare current pattern also be similarly structured. However, there is no compelling evidence for such fine-scale structuring in flaring active regions, and indeed such fine structure is difficult to maintain against resistive diffusion for the many hours/days prior to the flare itself. Furthermore, *Yohkoh* observations have clearly shown that many flares result when

regions of *large-scale* bulk shear interact, and it would be indeed mysterious if such an interaction were to produce a flare when substructure on similar interaction scales did not. A resolution of this apparent paradox is that fine-scale restructuring of the current pattern happens as a result *of the flare itself*, with such a large number of channels, the current per channel is only of order 10^{11} statamps. Such a current can be "turned on" in a second or so with a voltage of order

$$L \frac{dI}{dt} = \frac{l}{c^2} \frac{I}{\tau} \approx 0.1 \text{ statvolts} \sim 100 \text{ V}.$$

This is well within the permitted bounds, so that the usual high-inductance arguments (e.g., Holman 1985) do not hold. However, this result does have profound implications not only for the flare mechanism but also for the means by which such a finely-scaled current pattern closes.

The problem of current closure of such highly structured currents has been addressed and essentially solved (Emslie and Hénoux 1995, *Ap.J.*, **446**, 371). The issue essentially reduces to finding a mechanism which can carry currents of the required magnitude across field lines from one channel (or sheet) into an adjacent one - only in this way can a current pattern can be developed which, although complex, not only accounts for the large number of electrons required to produce a hard X-ray burst, but is also consistent with the demands of electrodynamics and the structure of the preflare active region. Cross-field currents carried by electrons are difficult to drive because the electrons are highly magnetized. However, the ions are much less magnetized and can move perpendicular to field lines for the small distances appropriate to the current channel/sheet widths discussed above without essential difficulty. It follows that such cross-field ion drifts can effectively complete the current circuit. Our model utilizes the constant dynamic balance between ionization and recombination of hydrogen in the upper chromosphere. Electrons arriving at the chromosphere in one current channel or sheet recombine with ambient protons, while, at the same time, spontaneous ionization of hydrogen atoms at the base of an adjacent current channel provide electrons that flow in the opposite direction. The protons on the second field line migrate to the first (thereby closing the current), while the (unmagnetized) hydrogen atoms drift from the first field line to the second in response to cross-field pressure gradients.

We have solved quantitatively for the current structure, taking into account not only the distribution of cross-field current with depth but also the fate of electrons that "undershoot" or "overshoot" the layer most propitious for current closure, and concluded that the mechanism is indeed a viable one.

(2) The Role of Nonthermal Protons in the Flare Energy Budget

A large fraction of our work over the past year has concentrated on the role of nonthermal protons in the impulsive phase of solar flares. It has been suggested by Ramaty et al. (1995, *Ap.J.*, **455**, L193) that the high observed fluxes in the low-excitation-threshold 1.634 MeV line of ^{20}Ne indicate that the energy spectrum of protons in the $\sim\text{MeV}$ range may be much steeper than previously supposed. They in turn suggested that the energy content in such protons may be an order of magnitude greater than previous estimates. If true, this result implies a very significant role for proton energization in the impulsive phase of solar flares, possibly to the extent that the proton energy budget is comparable to that of the energetic, hard X-ray producing electrons that have long been held to be the dominant energetic component.

In a series of papers, we have critically examined the proton vs. electron energization issue. A comprehensive review article on electron and proton acceleration mechanisms and their relevance to the impulsive phase of solar flares (Miller, Cargill, Emslie, et al. 1997, *JGR*, **102**, 14631) was published. More specifically, we have shown (Emslie et al. 1996, *Ap.J.*, **470**, L131) that $\sim\text{MeV}$ protons deposit their energy in just the right part of the solar atmosphere to account for the large increase in soft X-ray emission measure (through heating of chromospheric plasma from temperatures of $\sim 10^4$ K to $\sim 10^7$ K) that is such a necessary requirement of any energy transport model in flares. Encouraged by this result, we conducted (Emslie, Mariska, and Montgomery 1998, *Ap. J.*, **498**, in press) a series of detailed hydrodynamic models of the atmospheric response to proton bombardment, for comparison with observational diagnostics such as soft X-ray line profiles. We found that, due to fact that the velocity of the target protons is comparable to the thermal velocity of the ambient electrons, the energy loss rate of protons in the resulting "warm target" corona is much less than that in the usually-assumed cold target approximation. Consequently, not only is the heating rate much less but the proton spectrum is remarkably uniform throughout the coronal region, leading to a similarly uniform heating rate. This in turn creates lower pressure gradients and so much smaller velocities in evaporated plasma, more consistent with the observed small blueshifts in the centroids of soft X-ray emission lines.

We have also (Emslie, Brown, and MacKinnon 1997, *Ap. J.*, **485**, 430) critically reexamined the Ramaty et al. (1995) conclusions by including the effects on the energy loss rate of protons in a (warm, ionized) coronal target, as opposed to the cold, neutral target assumed by Ramaty et al. We found that the conclusions regarding the importance of $\sim\text{MeV}$ protons in the flare energy budget are actually *enhanced* by these considerations.

(3) Spatial Aspects of The Hard X-Ray/Soft X-Ray Relationship

There has recently been a great deal of interest in flares exhibiting “loop-top” hard X-ray sources (e.g., Masuda et al. 1994, *Nature*, 371, 495). We have used existing models of the hydrodynamic response of the solar atmosphere to impulsive energization to predict the time dependence of the hard X-ray flux in coronal and chromospheric regions of the loop. The purpose of this analysis was to ascertain the validity of the “Neupert Effect” (wherein the hard X-ray flux is proportional to the time derivative of the soft X-ray flux) at the various separate locations. We found (Li, McTiernan, and Emslie 1998, *Ap.J.*, 491, 395) that while the Neupert effect is satisfied for *spatially-integrated* emission, it does *not* hold for the emission from either loop-top or the footpoint components individually. Neither do the time variations of hard and soft X-ray fluxes correspond to recent observations (Hudson et al. 1994, *Ap. J.*, 422, L25) of “impulsive” soft X-ray emission from the loop footpoints. The implications of this result for impulsive phase energy transport models are currently being investigated.

(4) Bremsstrahlung Emission from a Nonuniform Target

The solar atmosphere is characterized by a steep gradient in density, temperature, and ionization level in passing from the corona to the chromosphere. The abrupt change in ionization level, through the Coulomb logarithm, causes a similarly abrupt change in the energy loss rate of nonthermal electrons, and so an increased efficiency of hard X-ray production. Consequently, actual injected electron spectra may be significantly different from those inferred from a straightforward (uniform target) thick-target analysis of the emitted hard X-ray bremsstrahlung. Brown, Emslie et al. (1998, *Solar Phys.*, in press) have explored the relation between the actual and “uniform-target” electron spectra, finding fascinating examples of nonuniqueness (even for perfect data) in the solution and the possibility that “upturns” in the inferred spectra may be artifacts of the uniform target assumption. Resolution of nonuniqueness issues is only possible with spatially resolved hard X-ray spectra, such as from the HESSI mission.

**THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
DEPARTMENT OF PHYSICS**

COLLOQUIUM

**Optics Building, Room 234
Tuesday, April 14, 1998**

**2:15 P.M. - Refreshments
2:30 P.M. - Seminar**

LASER WAKEFIELD ACCELERATION AND ASTROPHYSICAL APPLICATIONS

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ABSTRACT

High intensity laser makes self-induced high electromagnetic field in matter. Recent developments of Chirped Pulse Amplification permit Petawatt laser at Lawrence Livermore National Laboratory's NOVA facility. Acceleration of electrons seems reaching 3 GeV/cm, or $> 10^{20}$ g, comparable to the general relativistic phenomena around the Schwarzschild radius of a black hole. Electrons from Hawking radiation should be experiencing this acceleration. The LLNL-UAH-MSFC-Davis-MIT experiments made preliminary experiments with 10^{20} Watts/cm² pulse, which is hitherto the highest energy density regime of non-linear relativistic optics. Some applications to Astrophysics with table-top Terawatt lasers have been considered for astrophysical applications. Physics in the Non-linear QED regime, $> 10^{30}$ W/cm², will be briefly discussed.